Marine Physical Laboratory

Nonlinear Signal Classification Using Dynamical Systems Theory

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The long range goal of this project was the development of new signal processing and data classification methods based on ideas from the field of nonlinear dynamics. Specifically, nonlinear time-domain modeling methods using closed-form dynamical equations were to be formulated in a rigorous way in the framework of standard statistical signal classification methods. The aim was to provide new algorithms and automated tools which could enhance existing Navy systems for Sonar detection and classification, and to eventually transition them to the fleet.

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Introduction

This document represents the final report for the research project entitled "Nonlinear Signal Classification using Dynamical Systems Theory", ONR Grant N00014-99-1-0072, conducted by Dr. Jim Kadtke at the Marine Physical Laboratory in San Diego, California. This project was a follow-on award for a previous grant of the same title, and was intended to continue and extend that research agenda. The start and end dates for this project were 1 October 1999 through 30 September, 2001 respectively. The research objectives and major results obtained during the program are summarized below, in the format specified by ONR for standard year-end reports.

Long-Term Research Objectives

The long-term goal of this research project since its inception was the development of new signal processing and data classification methods based on ideas from the field of nonlinear dynamics. Specifically, nonlinear time-domain modeling methods using closed-form dynamical equations were to be formulated in a rigorous way in the framework of standard statistical signal classification methods. The aim was to provide new algorithms and automated tools which could enhance existing Navy systems for Sonar detection and classification, and to eventually transition them to the fleet. Also, this project supported with theoretical research a second ONR research program under Dr. John Tague, which focused on the practical design and validation of dynamical classifiers.

During the initial grant period, significant results were obtained on understanding the properties of differential equations as signal classifiers, both from an analytic and a computational viewpoint. Within this last two-year program period, the focus shifted towards developing methods for calculating optimal dynamical signal models for given data sets, and also for adapting numerical methods to improve overall classification performance. These results are summarized in the remaining part of this report.

S&T Objectives

Under the original research program, we sought to develop new time-domain signal models based on closed-form nonlinear dynamical systems, and we developed techniques based on delay-differential equations. We also developed numerical processing schemes to utilize these models along the lines of standard signal processing algorithms, and to assess their usefulness by generating standard performance measures such as ROC curves. We then sought to characterize their performance on real-world data sets, such as Sonar and bio-sonar data obtained from US Navy and other sources.

In the most recent two-year program period, we attempted to refine these methods by developing schemes for deriving "optimal" signal models which could provide enhanced performance over the generic models which we had previously utilized. We also developed some data processing methods such as bandwidth normalizers to pre-process the data and improve performance, which were specifically designed to operate with dynamical based methods. We then implemented some novel feature space discrimination methods, for example probabilistic neural networks, to

additionally improve performance by providing superior methods for signal class separation. Finally, we tested these improvements by re-analyzing a data set of dolphin echolocation chirps provided by SPAWAR.

Approach

The fundamental technique we developed was a method whereby the unknown coefficients of a dynamical signal model could be reliably and robustly estimated from observed signals, and used to generate classification features for Navy detection and classification applications. This method allows the unknown model coefficients to be expressed as functions of generalized signal correlations, in much the same way that the Yule-Walker equations are used for AR modeling methods. This method has the great advantage of typically providing closed-form analytic expressions for the unknown coefficients, for general classes if input data. This has allowed us to investigate the convergence properties and signal discrimination in a rigorous fashion. We have been able to identify correlation functionals which are explicitly included in continuous dynamical models which do not exist in standard signal models, and which thereby can add new classification information. We have used this formalism to generate theoretical performance estimates for idealized signal classes, and to design optimal 'dynamical detectors'. We have also applied the general classification ideas to a few real data sets to assess the methods performance.

Within the last two-year program period, we desired to improve the classification performance by deriving dynamical models which were specific to particular data sets. We pursued two main methods: that of calculating orthogonolized model expansions using a Gram-Schmidt technique, and the use of a specially-formulated genetic algorithm which can search for an optimal model in an automated fashion. Both of these methods greatly improved the ability to model nonlinear data sets, although we found that classification performance can occasionally depend on other issues not directly related to the data model.

We also attempted to improve the performance of the dynamical methods by adapting known pre- and post-processing methods specifically for a dynamical paradigm. For pre-processing of data, we developed data normalizers which allowed us to filter out corrupting signal components, while at the same time retaining the high dimensionality required for the dynamical classifiers. In terms of post-processing, we investigate several methods to improve discrimination in the feature space of the dynamical classifiers, since the dynamical features often are distributed in a non-Gaussian fashion. We determined that probabilistic neural networks provided the best discrimination of signal classes when these features are not simply connected.

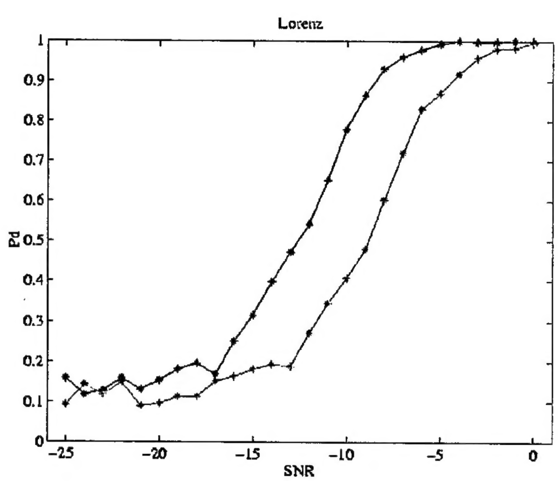
Finally to test the overall performance of the dynamical classification schemes, we analyzed data sets of dolphin acoustic echolocation data provided to us by SPAWAR. During the previous program period, we obtained very poor performance on this data set, however the improved techniques developed during the latter program period provided excellent discrimination.

S&T Completed

During the first program period, we formulated a model estimation procedure for delay-differential equations into a rigorous framework for classification purposes. We calculated theoretical feature distributions for a variety of idealized signal classes. We developed a pre-processor to determine if a dynamical model is useful on a given data set, by evaluating the dynamical correlation functions. We also demonstrated that these features provide detection/classification performance beyond that achievable by standard spectral or energy methods, by calculating ROC curves using a generalized Mahalanobis distance classifier. We also demonstrated improved detection performance on two real data sets of broadband, low-SNR signals from sea tests.

In the most recent program period, we achieved several important results which we believe make the dynamical classification methods applicable to real-world data processing applications. Firstly, we demonstrated that new pre-processing normalizers are capable of spectrally removing most types of signal clutter while at the same time maintaining high-dimensionality of the signal, thereby allowing the dynamical models to accurately represent the remaining signal with respect to a background noise process.

Secondly, we were able to demonstrate that dynamical signal models (i.e. delay-differential equation models) could be calculated which were specific to a given signal class. Gram-Schmidt orthogonalization provides one such method, and can result in enormous classification performance increases (up to 15 dB), however this technique tends to be "brittle" with regards to variations in observed data. Model selection using a genetic algorithm was found to provide a much more robust method, however overall improvement in classification performance proves to be less using this technique (on the order of 5-6 dB). An example of this detection performance improvement is given in Figure 1 below, which shows a ROC curve for a generic signal model (red), and for a signal-specific model calculated with the genetic algorithm using our automated search algorithm (blue). Both were calculated on the identical data sets.



Generic Signal Model

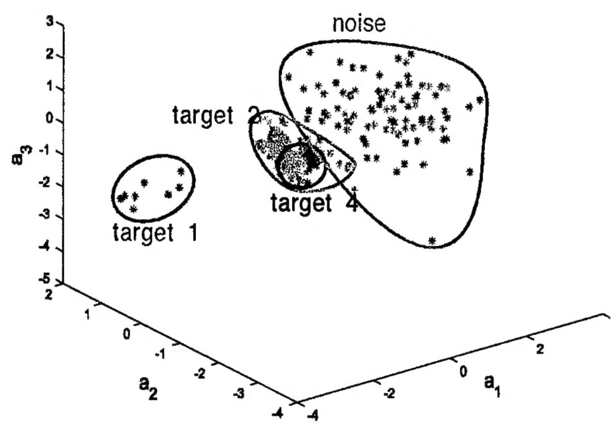
$$dx/dt = a_1 x_{\tau_1} + a_2 x_{\tau_2} + a_1 x_{\tau_1} x_{\tau_2}$$

Genetic Algorithm Derived Model

$$dx/dt = a_1 x_{\tau_1} + a_2 x_{\tau_2} + $$
$$+ a_3 x_{\tau_2}^2 + a_4 x_{\tau_1}^3 + a_5 x_{\tau_1}^2 x_{\tau_2}$$

Thirdly, because the feature distributions for dynamical models are sometimes distributed in a non-simply connected fashion, we adapted new feature discrimination methods to improve performance during post-processing. The most powerful technique we developed utilized probabilistic neural networks, which provides feature partitioning via a radial basis function expansion. This method proved able to discriminate feature distributions from different signal classes even when they were quite non-Gaussian.

Finally, as a test bed for the new techniques developed under this program period, we analyzed a data set of dolphin acoustic echolocation data provided by SPAWAR. This data set consisted of trains of echolocation pulses which were categorized according to target geometry. During the previous program period, we were not able to effectively discriminate the different signal classes using the more basic dynamical classifiers. However, using the improvements developed during this program period, we were able to generate near-perfect discrimination of these different signal classes. Figure 2 shows the feature distributions and classification table for these results.



class 1	class 2	class 1 identified as		class 2 identified as	
		class 1	class 2	class 1	class 2
target 1	target 2	100 %	0 %	0 %	100 %
target 1	target 4	100 %	0 %	0 %	100 %
target 2	target 4	94 %	6 %	33 %	67 %
target 1	noise	100 %	0 %	0 %	100 %
target 2	noise	100 %	0 %	0 %	100 %
target 4	noise	100 %	0 %	0 %	100 %

Impact/Navy Relevance

This research provides perhaps the first method to embed a nonlinear dynamical processing technique within a rigorous statistical discrimination framework, and to analytically calculate the theoretical detection/classification performance. It is clear from several examples on simulated and real-world data sets that these "dynamical classifiers" provide enhanced performance over existing methods on certain classes of data. Since the estimation procedure is generally fast and robust, adaptation into existing Navy processing schemes should be straightforward, and should produce enhanced detection/classification performance in many applications. These applications should include data classes which are particularly difficult for conventional energy or spectral classifiers to process, for example quasi-broadband signals produced by low-dimensional dynamical processes, such as machine resonances. What remains is to provide for validated testing in a real-world setting in conjunction with Navy researchers.

Planned S&T Research Efforts

No further research is planned at this time due to termination of the program.

Technology Transfer

At present, we are continuing to interface with the ONR passive sonar program to attempt to define a transition path for the dynamical classifiers to the 6.2/6.3 arena. This will primarily involve an assessment on real world data sets, which is being coordinated in conjunction with NUWC researchers. This technology has also drawn considerable interest from other DoD organizations, particularly the Army acoustic classification program.

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Other Sponsored Science and Technology

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Subcontracts:

No subcontracts.

Journal Publications Appearing in Print

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Formal Technical Reports Released by Institution

none

Informal Technical Reports

1. Numerical tests for the influence of a disturbing narrow-band signal on the model parameter distributions

2. A detection study of hydroacoustic signals recorded at a sea trial in the Baltic Sea

Recent Presentations

1. R.K. Lennartsson and J.B. Kadtke, "Using nonlinear dynamical signal models for detection and classification of real-world data," 3rd International Conference on Marine Electromagnetics, MARELEC 2001, Stockholm, Sweden, July 2001.

2. R.K. Lennartsson and J.B. Kadtke, "Detection and classification of real-world data using nonlinear dynamical signal models," 6th Experimental Chaos Conference, Potsdam, Germany, July 2001.

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